

Near Infrared Observations of Galactic Black Hole Candidates^{*}

S. Chaty^{1,2}, I.F. Mirabel^{2,3}, P. Goldoni², S. Mereghetti⁴, P.-A. Duc², J. Martí⁵, R.P. Mignani⁶

¹ *Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom†*

² *Service d'Astrophysique, DSM/DAPNIA/SAP, CEA/Saclay, L'Orme des Merisiers, Bât. 709, F-91 191 Gif-sur-Yvette, Cedex, France*

³ *Instituto de Astronomía y Física del Espacio C.C. 67, Suc. 28. 1428, Buenos Aires, Argentina*

⁴ *Istituto di Fisica Cosmica "G.Occhialini", via Bassini 15, I-20133 Milano, Italy*

⁵ *Departamento de Física, Escuela Politécnica Superior, Universidad de Jaén, Calle Virgen de la Cabeza, 2, E-23071 Jaén, Spain*

⁶ *ESO, Karl-Schwarzschild Strasse 2, D-85748 Garching-bei-München, Germany*

Received / Accepted

ABSTRACT

We report on several European Southern Observatory (ESO) near-infrared (NIR) observational campaigns aimed at understanding the nature of galactic black hole candidates. Our results, including NIR photometry of the sources GRO J1655-40, GRS 1739-278, GRS 1716-249, GRS 1121-68 and GX 339-4, show that all the sources but GRO J1655-40 are consistent with low-mass stars as the companion star of the binary system.

By locating the counterparts on a colour-magnitude diagram (CMD), we better constrain the spectral type of the companion star of three of the systems considered here, and confirm a fourth one. The spectral types are respectively: M0-5 V for GRS 1716-249, F8-G2 III for GX 339-4 and later than F5 V for GRS 1739-278. We confirm the already known spectral type of the companion in GRS 1121-68 (K0-5 V). The location of GRO J1655-40 on the CMD is consistent with the sub-giant luminosity class and with this source crossing the Hertzsprung gap. However, a non-stellar emission seems to contribute to the NIR flux of this source.

Key words: stars: individual: GRO J1655-40, GRS 1739-278, GRS 1716-249, GRS 1121-68, GX 339-4, infrared: stars

1 INTRODUCTION

Optical follow-up observations of transient X-ray sources are fundamental to fully understand the nature of these systems and characterize the accretion. Most important, the measurement of their mass function through optical observations performed in quiescence is the best way to confirm the presence of a black hole (see e.g. Charles 1999). Most of the bright transient X-ray sources discovered in recent years are located in the Galactic Bulge region. Owing to the strong absorption present along this direction of the Galaxy, NIR observations are one of the best ways of constraining the properties of these systems. Furthermore, the disk emission is much weaker in the NIR band allowing a much better probe of the nature of the companion star. One approach is

to perform spectroscopic observations (see e.g. Bandyopadhyay et al. 1999), but for faint sources or for the sources lacking prominent emission lines, photometric observations are more efficient for deriving the NIR spectral energy distribution of the source (see e.g. Chaty et al. 1996).

We observed the infrared counterparts of several galactic bulge hard X-ray sources, in order to better constrain the spectral type of the mass donor star. Here we report on our results on five galactic black hole candidates: GRO J1655-40, GRS 1739-278, GRS 1716-249, GRS 1121-68 and GX 339-4. Since all the sources we observed show variations, we concentrate on the magnitudes obtained around the emission minimum of our observations. Assuming that all the emission at this time came from the photosphere of the companion star, we can compare our data with infrared magnitudes of different stellar spectral types. Any anomalous colour distribution can then be related to the source spectral state, known from high energy observations. Obviously, this method has limitations, since the infrared flux may be contaminated. There are a number of

^{*} Based on observations collected at the European Southern Observatory, La Silla, Chile (proposals: 51.6-0018, 53.6-0015, 59.D-0719 & 61.D-0542).

† S.Chaty@open.ac.uk

possible sources of contamination: emission from the accretion disk; X-ray heating of the secondary; the presence of ejected material, as was the case during flares of the superluminal source GRS 1915+105 (Mirabel et al. 1998); the presence of surrounding dust or of an extended atmosphere. Nonetheless, since the emission provides at least an upper limit to the source flux, this constrains the nature of the companion star, and in addition can also give some information regarding sources of contamination.

In Section 2 we describe our method, and then go through each source in turn, summarizing the current knowledge and describing our observations and results. Discussion of the results and conclusions are in Section 3. Some of the results presented here were partly reported in Chaty (1998).

2 OBSERVATIONS AND RESULTS

The general parameters of these sources, including the distance and the absorption that will be used in this paper, are given in Table 1. In Table 2 we give a log of the observations that were mostly obtained at the ESO/MPI (Max Planck Institute) 2.2 m telescope in La Silla (Chile) using the IRAC2b camera. The IRAC2b camera, mounted at the F/35 infrared adapter of the telescope, is a Rockwell 256×256 pixels Hg:Cd:Te NICMOS 3 infrared array detector. It was used with the lens C, providing an image scale of 0.49 arcsec/pixel and a field of 136×136 arcsec². The typical seeing for these observations was 1.2 arcsec.

Each final image is the result of the median-filtering of at least 9 frames of 1 minute exposure each (depending on the observations). An image of the sky was taken after each image of the object (offset by 30''), to allow subtraction of the infrared sky emission. The images were further treated by removal of the dark current and correction with a dome flat field, and we carried out absolute photometry by calibration obtained with the observation of different standard stars. This work was performed with the IRAF procedures, using the DAOPHOT package for photometry in crowded fields.

To estimate the nature of the companion stars, we compare their NIR absolute magnitudes with those of template stars, using the relations between the magnitudes and the spectral type reported by Ruelas-Mayorga (1991) and Johnson (1966). Absolute magnitudes have been computed from the distances reported in Table 1, and correction of the reddening has been estimated from the absorption measured either from X-ray or optical observations, based on the relation $A_V(\text{mag}) = 5.59 \times 10^{-22} N_H (\text{cm}^{-2})$ (Predehl & Schmitt 1995). The absorption in the infrared bands J, H and K is given by $\frac{A_J}{A_V} = 0.282$, $\frac{A_H}{A_V} = 0.175$ and $\frac{A_K}{A_V} = 0.112$ (Rieke & Lebofsky 1985). We report the absolute infrared magnitudes of our targets on a CMD in Figure 1. We report in Figure 2 the X-ray lightcurves of the sources as observed by the All Sky Monitor (ASM) of the Rossi X-ray Timing Explorer (*RXTE*) in the interval of our observations.

2.1 GRO J1655-40

2.1.1 Introduction

GRO J1655-40 (Nova Scorpii 1994) was discovered with BATSE as a hard X-ray Nova (Zhang et al. 1994) and was the second superluminal source to be discovered in the Galaxy (Hjellming & Rupen 1995). The column density was estimated to be in the range $3 - 8 \times 10^{21} \text{ cm}^{-2}$ (Hynes et al. 1998, Inoue et al. 1994, Greiner 1996, Inoue et al. 1995). Following Hynes et al. (1998), we adopt the intermediate ASCA measurement of $N_H = 4.4 \times 10^{21} \text{ cm}^{-2}$ (Nagase et al. 1994). Assuming a mean extinction along the line of sight, the distance of the source has been estimated as 3 kpc (Greiner 1996). GRO J1655-40 has a bright variable optical counterpart (Bailyn et al. 1995): $B \sim [19 - 18.4]$, $V \sim [17.4 - 16.8]$, $R \sim [16.4 - 15.8]$ and $I \sim [15.4 - 14.8]$ (Orosz & Bailyn 1997, Greene et al. 2001). Comparing the spectrum of the source in quiescence with many standard stellar spectra of type M and K, the companion star was estimated to have a spectral type F3-F6. Following arguments on the size of the star compared to its Roche lobe, it was argued that the star was a sub-giant (Orosz & Bailyn 1997).

The masses of the two components of the system have been precisely determined thanks to optical observations: the compact object mass is in the range $4.1 - 7.9 M_\odot$ (see Phillips et al. 1999, Shahbaz et al. 1999 and Soria et al. 1998), making GRO J1655-40 a very good black hole candidate while the secondary star mass was estimated at $1.7 - 3.3 M_\odot$, both with 95 % confidence (Shahbaz et al. 1999). The spectroscopic period is 2.62157 ± 0.00015 days (Orosz & Bailyn 1997), with a radial velocity semi-amplitude of $K = 215.5 \pm 2.4 \text{ km s}^{-1}$ and a mass function $f(M) = 2.73 \pm 0.09 M_\odot$ (Shahbaz et al. 1999). The position of the secondary on the Hertzsprung-Russell diagram has been claimed to be consistent with a star of $\sim 2.3 M_\odot$, which evolved from the main sequence, and is now mid-way between the main sequence and the beginning of the giant branch (Kolb et al. 1997).

2.1.2 The observations

As it has a bright optical counterpart, GRO J1655-40 has not been studied in great detail in NIR. In Table 2 we present the only NIR photometry which has been reported for this source, the counterpart being seen in the three filters. Our 1997 observations were performed at the end of an X-ray outburst (see Figure 2), consequently the NIR emission is likely contaminated by an external source. We take therefore the magnitudes corresponding to the observations in an almost quiescent state by Greene et al. (2001). The absolute magnitudes are $M_J = 0.77 \pm 0.15$ and $M_K = 0.59 \pm 0.15$, the error quoted being due to the ellipsoidal variation.

We can see in Figure 1 that the colours and magnitudes of the source in quiescence locate it on the CMD between the main sequence and giant star branches. This is therefore consistent with the sub-giant luminosity class derived by Orosz & Bailyn (1997) and also with the fact that the source is crossing the Hertzsprung gap. However, the position in the CMD shows a discrepancy with the F3-6 spectral type mentioned earlier. Therefore, there is an emission which is not of stellar origin in the NIR emission of GRO J1655-40.

Source	gal. coord.	$L_{2-10\text{keV}}$ erg s^{-1}	L_{opt} (m_V mag)	$L_{6\text{cm}}$ (mJy)	Period	Distance (kpc)	N_H (10^{22}cm^{-2})	A_V (mag)
GRO J1655-40 Nova Scorpii 94	$l^{II} = 344^\circ 98$ $b^{II} = +2^\circ 46$ bai95	2×10^{37} gre96a	[17.4-16.8] oro97	[0-2500] hje95	2.62157d ± 13 s oro97	3.0 gre96a	[0.3/0.8] 0.44 nag94	2.46
GRS 1739-278	$l^{II} = 0^\circ 66$ $b^{II} = +1^\circ 17$ mar97	5×10^{37} gre96b	23.2 ± 0.3 mar97	[1.1-4.7] hje96	-	8.5 mar97	[1.1/4.8] 2.0 gre96b/bor96	11.18
GRS 1716-249 Nova Ophiuchi 93	$l^{II} = 0^\circ 20$ $b^{II} = +6^\circ 99$ del94	2×10^{38} del94	16.65 del94	[0.5-4.4] ± 0.1 del94	$\sim 14.7\text{h}$ mas96	[2/2.8] 2.4 del94	0.4 tan93	2.24
GRS 1121-68 Nova Muscae 91	$l^{II} = 295^\circ 30$ $b^{II} = -7^\circ 07$ del 91	10^{37} del 91	[20.35-13.3] ± 0.05 mcc92/del91	[3-137] kes91	10.5h bai92	[1.4/4] 2.8 del91/sha97	0.22 gre94	1.23
GX 339-4 4U 1658-48	$l^{II} = 338^\circ 94$ $b^{II} = -4^\circ 33$ dox79	2×10^{36} rub98	[21-15] dox79/gri79	[0-6.5] fen97	14.8h cal92	[5.6/7] 5.6 sha01	0.6 pre91	3.72 zdz98

Table 1. Parameters of the sources: coordinates, fluxes in different energy domains, orbital period when known, distance, hydrogen column density N_H and absorption A_V . The variations, if any, are given by $[min-max]$. The error is given in the following line. The reader should refer to Table 2 to see the NIR variations of these sources. Concerning the distance and column density, we reported the interval in which they are constrained, including the error, by $[min/max]$, and the value chosen in this paper is given in the following line. The references are: bai92: Bailyn 1992, bai95: Bailyn et al. 1995, bor96: Borozdin et al. 1996, cal92: Callanan et al. 1992, del91: Della Valle et al. 1991, del94: Della Valle et al. 1994, dox79: Doxsey et al. 1979, fen97: Fender et al. 1997, gre94: Greiner et al. 1994, gre96a: Greiner 1996, gre96b: Greiner et al. 1996, gri79: Grindlay 1979, hje95: Hjellming & Rupen 1995, hje96: Hjellming et al. 1996, kes91: Kesteven & Turtle 1991, mar97: Martí et al. 1997, mas96: Masetti et al. 1996, mcc92: McClintock et al. 1992, nag94: Nagase et al. 1994, oro97: Orosz & Bailyn 1997, pre91: Predehl et al. 1991, rub98: Rubin et al. 1998, sha97: Shahbaz et al. 1997, sha01: Shahbaz et al. 2001, tan93: Tanaka 1993, zdz98: Zdziarski et al. 1998.

Source	Date	JD	Tel	ref	$J(1.25 \mu\text{m})$	$H(1.65 \mu\text{m})$	$K(2.2 \mu\text{m})$
GRO J1655-40	19/07/97 07-10/99	2 450 648 2 451 421	2.2 CTIO	gre01	13.43 ± 0.03 13.7 – 14	12.87 ± 0.02 -	12.07 ± 0.01 13.1 – 13.4
GRS 1739-278	01/04/96 20/07/97 07/07/98	2 450 174 2 450 649 2 451 001	2.2 2.2 2.2		16.3 ± 0.1 18.7 ± 0.6 ≥ 19.2	15.5 ± 0.2 - -	14.9 ± 0.1 15.4 ± 0.25 ≥ 18.4
GRS 1716-249	08/07/94 19/07/97 06/07/98	2 449 539 2 450 648 2 451 000	2.2 2.2 2.2		16.2 ± 0.3 19.4 ± 1.2 ≥ 19.38	- 19.2 ± 1 ≥ 18.72	15.5 ± 0.3 18.3 ± 1 ≥ 17.77
GRS 1121-68	07/07/94 18/02/95 19/07/97 06/07/98	2 449 540 2 449 766 2 450 648 2 451 000	2.2 AAT 2.2 2.2	sha97	17.5 ± 0.25 - - ≥ 17.5	- 17.12 ± 0.12 - 17.2 ± 0.5	16.7 ± 0.25 - 17.23 ± 0.25 ≥ 16.5
GX 339-4	03/06/93 04/06/93 06/07/94 08/07/94 19/07/97	2 449 141 2 449 142 2 449 539 2 449 541 2 450 648	2.2 2.2 2.2 2.2 2.2		- 16.2 ± 0.3 15.3 ± 0.1 15.4 ± 0.1 14.21 ± 0.03	- - 14.9 ± 0.1 - 13.13 ± 0.01	15.2 ± 0.3 - 14.5 ± 0.1 14.4 ± 0.1 12.41 ± 0.01

Table 2. Infrared observations of the sources. The exposure times were respectively 10, 10, 15 and 9 minutes in 1993, 1994, 1997 and 1998. The two magnitudes quoted for GRO J1655-40 in 1999 are the interval of the ellipsoidal variations. gre01: Greene et al. 2001; mar97: Martí et al. 1997; sha97: Shahbaz et al. 1997. 2.2: 2.2 m La Silla Telescope (ESO, Chile), with the instrument IRAC2b. AAT: 3.9 m Anglo-Australian Telescope (AAT), with the infrared array IRIS. CITO: Cerro Tololo Inter-American Observatory, with ANDICAM on the 1.0 m Yale telescope.

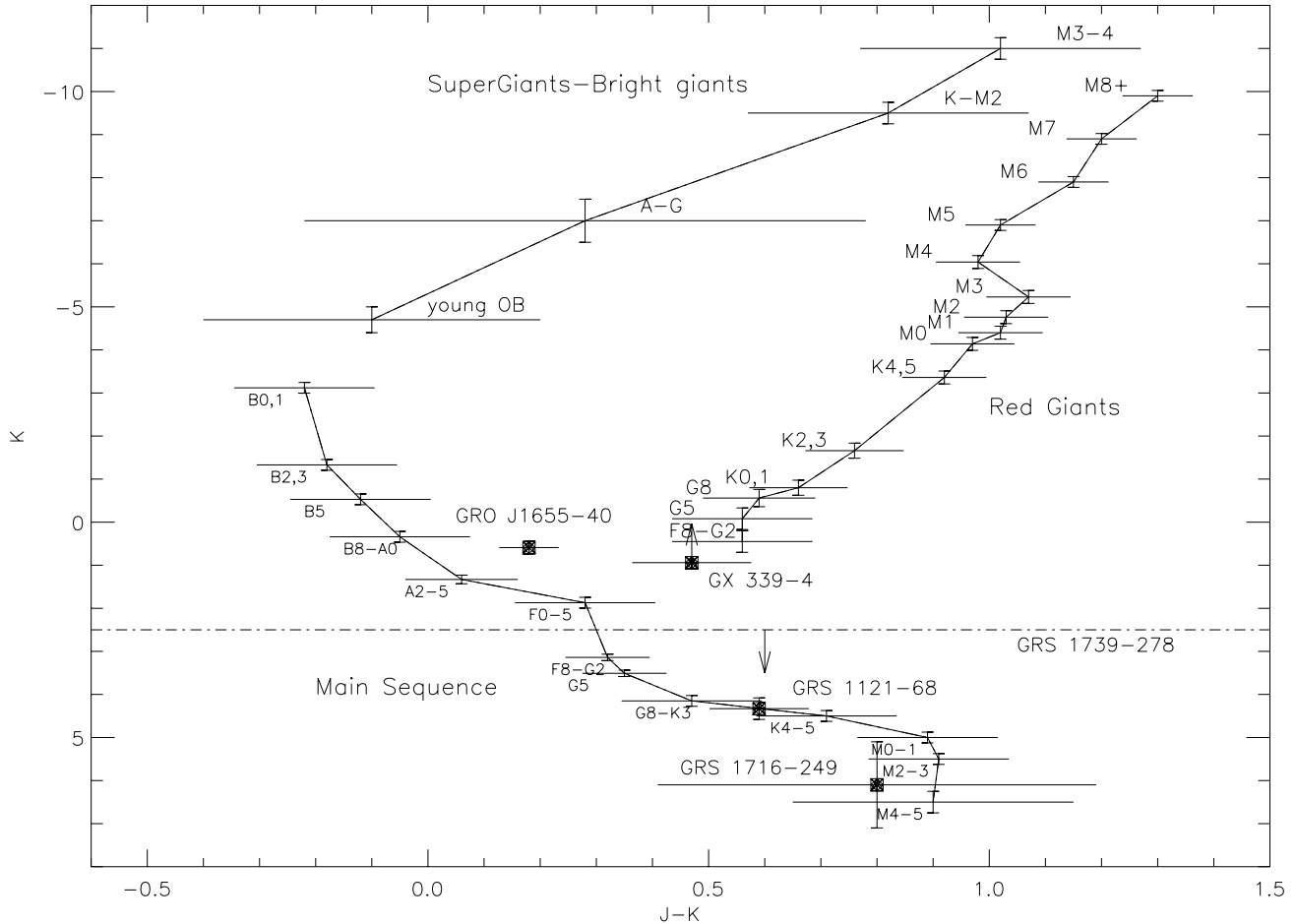


Figure 1. Near-infrared colour-magnitude diagram of galactic stars (Ruelas-Mayorga 1991), with the superimposed counterparts of GRO J1655-40, GX 339-4, GRS 1716-249 and GRS 1121-68. The error bars on GRO J1655-40 are due to the ellipsoidal variations, and the position of GX 339-4 corresponds to the lower limit of the distance. The dash-dot line is the upper limit for GRS 1739-278 (see section 2.2.2). This diagram shows that except for GRO J1655-40, which is consistent with an intermediate mass system, all sources are consistent with low mass systems.

Furthermore, this emission does not seem to be due to irradiation since the ellipsoidal lightcurve of the 1999 observations is well fitted by a model without any disk (Greene et al. 2001). This discrepancy was also pointed out by Beer & Podsiadlowski (2001) in their recent analysis of its quiescent light curve. Monitoring of the NIR emission during different states of activity of this source will be necessary to reveal the origin of this emission.

2.2 GRS 1739-278

2.2.1 Introduction

GRS 1739-278 is a hard X-ray transient source, discovered by SIGMA on 1996, March 18th (Paul et al. 1996). The hardness of its spectrum immediately suggested that it was an X-ray nova containing an accreting black hole. GRS 1739-278 seems to be located near the galactic center, therefore at the distance of ~ 8.5 kpc (Martí et al. 1997). Vargas et al. (1997) inferred a peak luminosity of $8.6 \pm 2.0 \times 10^{36}$ erg s $^{-1}$ in the 40-300 keV energy band. A variable radio source in

the hard X-ray error box was proposed as the counterpart of GRS 1739-278 (Hjellming et al. 1996). A candidate optical/infrared counterpart was soon discovered at the position of the radio counterpart with a constant luminosity in a range of 0.2 magnitudes on a timescale of several weeks during 1996 (Mirabel et al. 1996). The observed optical magnitudes of GRS 1739-278 are $V = 23.2 \pm 0.3$, $R = 20.5 \pm 0.1$ and $I = 18.3 \pm 0.3$ (Martí et al. 1997). The magnitudes and colours of the companion star of GRS 1739-278 seemed to suggest either a low-mass X-ray binary with a giant companion, or a high-mass X-ray binary. The major problem in distinguishing between them was the great uncertainty in the value of the hydrogen column density (Martí et al. 1997). The GRS 1739-278 column density estimates range from $1.2 \pm 0.1 \times 10^{22}$ cm $^{-2}$ (Greiner et al. 1996) to $4.1 \pm 0.7 \times 10^{22}$ cm $^{-2}$ (Borozdin et al. 1996).

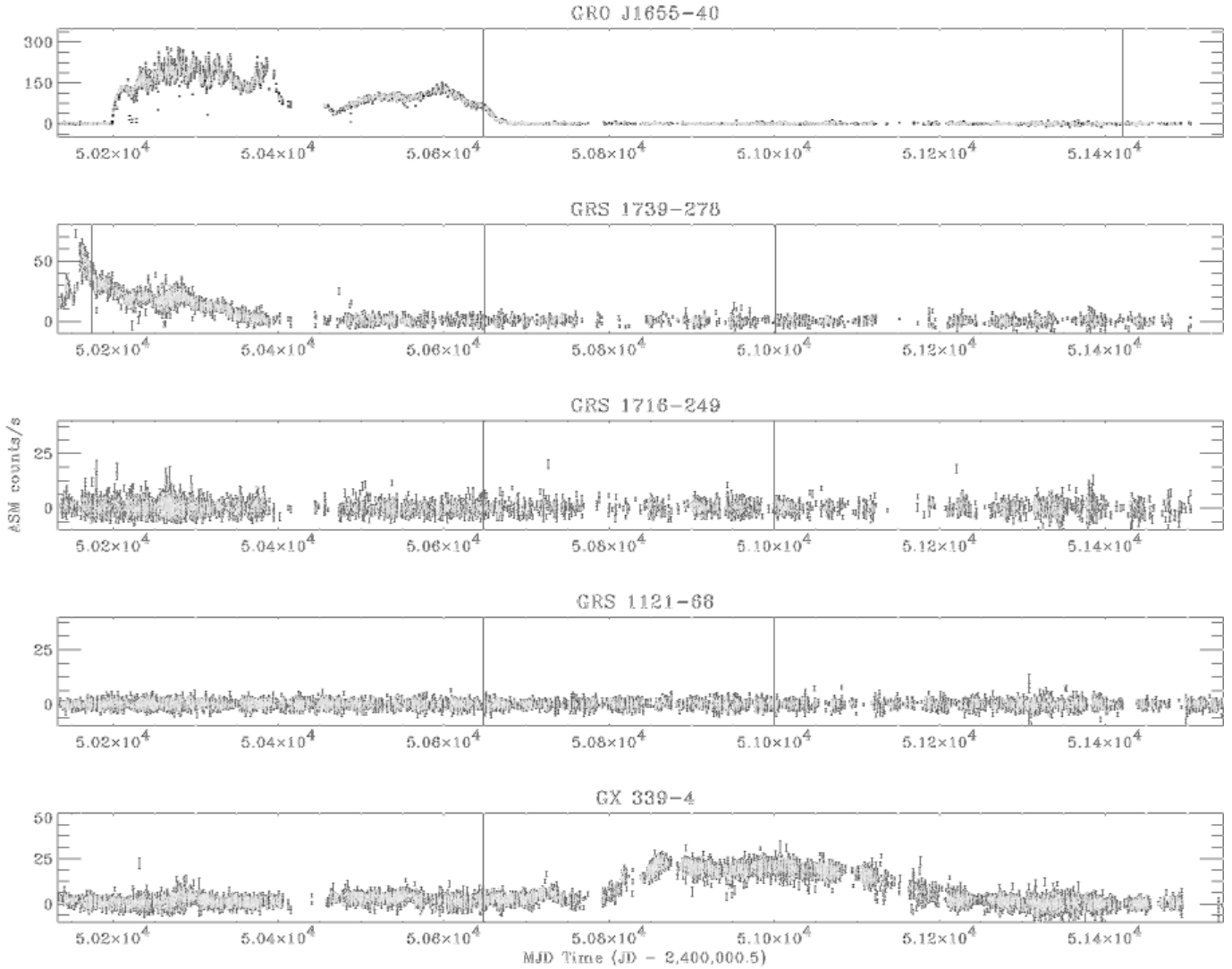


Figure 2. *RXTE/ASM* lightcurves of GRO J1655-40, GRS 1739-278, GRS 1716-249, GRS 1121-68 and GX 339-4 from 1996, February 20th to 1999, December 31st. These quick-look results show the observations in the high-energy band 2-12 keV. The time of observations are indicated by the vertical lines. For comparison, the Crab nebula flux is about 75 ASM counts/s. Concerning the uncertainties, the light curve of the Crab nebula gives a measure of the rms error of 5%. However, the error bars are an underestimate of the error, if sources present different spectral shape than the Crab, are located in crowded regions, and/or for different reasons. Therefore, we point out that, although we show here all the sources for completeness, there is no flux detected by the *ASM* from the sources GRS 1716-249 and GRS 1121-68 during the period of observation shown here.

2.2.2 The observations

The counterpart is confirmed by our observations, showing a continuous decline in the luminosity of this source (see Table 2). The source dropped by ≥ 3 magnitudes in both J and K between 1996 and 1998. For our analysis we will consider the magnitudes of 1998 as upper limits. Taking the assumed distance of $D \sim 8.5$ kpc, and the intermediate value of the column density $N_H = 2.0 \times 10^{22} \text{ cm}^{-2}$ (Martí et al. 1997), we can derive the absolute magnitudes respectively in the J and K bands: $M_J \geq 1.40$ and $M_K \geq 2.5$. J-K is not constrained; this source lies below the line $M_K = 2.5$ on the CMD (Figure 1). If GRS 1739-278's companion star is on the main sequence then it must be F5 V or later. By examining the optical and near-infrared colours of the system, Martí et al. (1997) derived two possibilities for the nature of the

secondary star: either a luminous early/middle B type main sequence star, or a middle G/early K giant star. Clearly, the implicit assumption by Martí et al. (1997) that the source had reached the quiescent level was premature at that time, and the magnitudes reported here allow us to better constrain the spectral type of this system.

2.3 GRS 1716-249

2.3.1 Introduction

GRS 1716-249 (Nova Ophiuchi 1993) is an X-ray transient source, detected on 1993, September 25th by SIGMA on GRANAT, and by BATSE on the γ -ray observatory Compton (GRO J1719-24) (Ballet et al. 1993). Its light curve during the flare was very similar to the one of GRS 1121-68,

and the (0.1-100 keV) X-ray luminosity at maximum was $L_X \sim 2.1 \times 10^{38} \text{ erg s}^{-1}$, which is close to the Eddington limit for a compact object of $1.6 M_\odot$. This X-ray luminosity is similar to those of A 0620-00 and of GRS 1121-68, both of which are, like GRS 1716-249, transient radio sources. ASCA observations gave an estimation of the column density of $N_H = 4 \times 10^{21} \text{ cm}^{-2}$ (Tanaka 1993). The optical counterpart was soon discovered (Della Valle et al. 1994). From $V = 16.65$ Della Valle et al. (1994) derived that the companion star was a low mass main sequence star of spectral type $\sim K$ or later. This classification was consistent with the photometric and spectroscopic properties of this object.

The distance of this source remains subject to uncertainties. Estimated from the equivalent width of the NaD absorption lines the derived distance is $D \sim 2 \text{ kpc}$, while taking the mean absolute magnitude at the maximum of the low mass X-ray binaries, the distance has been estimated to be $\sim 2.8 \text{ kpc}$, giving an absolute magnitude $M_V \geq 6$ (Della Valle et al. 1994). Masetti et al. (1996) discovered a superhump period at 14.7 hours, therefore indicative of the orbital period at a few percent accuracy. They estimated the mass respectively of the primary and the companion star to be $\geq 4.9 M_\odot$ and $1.6 M_\odot$. As noted by the authors, the secondary would then be substantially brighter than claimed by Della Valle et al. (1994), suggesting either the distance has been underestimated, or the secondary is a slightly evolved late type star.

2.3.2 The observations

GRS 1716-249 was not detected in our 1998 observations (see Table 2), which were less sensitive than the 1997 ones in which the source was still visible at faint fluxes. Other observations with more powerful telescopes are needed in order to see if GRS 1716-249 has now reached its minimum, or if its luminosity is still decreasing. We will take for this analysis the magnitudes of 1997, assuming that they correspond to a minimum. Adopting a distance of $D \sim 2.4 \text{ kpc}$ and a column density $N_H = 4 \times 10^{21} \text{ cm}^{-2}$, we can deduce the absolute magnitudes respectively in the J, H and K bands: $M_J = 6.9 \pm 1.2$, $M_H = 6.9 \pm 1$ and $M_K = 6.1 \pm 1$. This allows us to say that the counterpart is a main sequence star of spectral type M0-5 V. This is not consistent with the possible masses of the companion star derived by Masetti et al. (1996). It seems likely therefore that the secondary is a slightly evolved late type star. Therefore, our NIR absolute magnitudes are consistent with the absolute magnitude $M_V \geq 6$ of the optical counterpart identified by Della Valle et al. (1994), and furthermore allow us to constrain better the nature of the companion star.

2.4 GRS 1121-68

2.4.1 Introduction

This X-ray nova (Nova Muscae 1991) was discovered by Ginga on 1991 January 8th and by GRANAT on 1991 January 9th (Lund et al. 1991). The column density has been derived from ROSAT and Ginga observations: $N_H = 2.2 \times 10^{21} \text{ cm}^{-2}$ (Greiner et al. 1994). The optical counterpart was identified by Della Valle et al. (1991) with a star which rose from $R \sim 20$ to $V \sim 13.3$. The distance of this

object has been subject to many uncertainties. The estimation from $E(B-V)$ gives $D = 2.3 \pm 2.1 \text{ kpc}$, but using the linear relation between the equivalent width of the NaD line and the distance, a distance of $D = 1.4 \text{ kpc}$ could be derived (Della Valle et al. 1991). A distance of 2.8 kpc was estimated from observations in the H-band, with an upper limit of 4 kpc (Shahbaz et al. 1997). Optical observations in quiescence, when its magnitude after dereddening was $B_0 = 19.8$, showed that GRS 1121-68 is a low mass X-ray binary composed of a black hole of mass greater than $\sim 3 M_\odot$ and of a $0.7 M_\odot$ low mass companion of spectral type in the interval K0-4 V (Remillard et al. 1992). Further optical spectroscopic observations in quiescence suggested the donor star to be a low main sequence star of spectral type of K3-5 V (Orosz et al. 1996) and allowed the detection of a 10.5 hour orbital period (Bailyn 1992).

2.4.2 The observations

To estimate the nature of the binary system, we selected from Table 2 the magnitudes of the source near minimum luminosity, i.e. in 1994. Following Shahbaz et al. (1997), we choose 2.8 kpc as the most likely distance. The absolute magnitudes estimated in the J and K bands are respectively: $M_J = 4.92 \pm 0.25$ and $M_K = 4.33 \pm 0.25$. We can see on Figure 1 that the location of this point on the CMD is consistent with the companion star being a main sequence star of spectral type K0-5 V, so fully consistent with the previous spectroscopic observations. This shows that in the case where the NIR only comes from the companion star, i.e. when there is no contamination, this method can be efficiently used to constrain the spectral type of the companion star.

2.5 GX 339-4

2.5.1 Introduction

GX 339-4 was discovered in 1973 by the 1-60 keV X-ray MIT detector on the satellite OSO-7 (Markert et al. 1973). Because of its X-ray spectral behaviour similar to that of Cygnus X-1 and of its rapid temporal variations (from 0.010 to 10 s), GX 339-4 was classified as a black hole candidate (Tanaka & Shibazaki 1996). The counterpart of GX 339-4 was identified as a blue star of typical $V = 16.6$ magnitudes but variable between $15 < V < 21$ magnitudes (Doxsey et al. 1979, Grindlay 1979). A 14.8 hour modulation of the optical luminosity was interpreted as the orbital period of the binary system (Callanan et al. 1992). However, because of the substantial optical emission from the accretion disk, the orbital parameters of GX 339-4 have not yet been established in order to clearly demonstrate that it is a black hole binary: the estimated mass of the compact object is $\leq 2.5 M_\odot$ (Cowley et al. 1987).

Recent optical observations of GX 339-4 in an extended “off” state allowed to estimate a lower limit to the distance of 5.6 kpc and an evolved spectral type later than F8 (Shahbaz et al. 2001). Zdziarski et al. (1998) derived the extinction $E(B-V) = 1.2 \pm 0.1$ magnitudes which is equivalent to $A_v = 3.72 \pm 0.1$ magnitudes (see e.g. Cardelli et al. 1989).

2.5.2 The observations

The results (Table 2) show that the luminosity changed appreciably during this period: by 2 magnitudes in J; 1.8 in H; and ~ 2.6 in K. The X-ray activity is shown in Figure 2. We take the magnitudes corresponding to the minimum luminosity of this source in 1993, the two observations being taken with a one day interval. At this date the source was not detected with BATSE: the source was certainly in a low state (off state) or a low low-hard state (S. Corbel, private communication). Using the distance $D = 5.6$ kpc and an absorption of 3.72 magnitudes in the V-band, we obtain the absolute magnitudes respectively in the J and K-bands: $M_J = 1.41 \pm 0.3$ and $M_K = 1.04 \pm 0.3$.

From the location of GX 339-4 on the CMD, it appears that the companion star is a red giant of spectral type F8-G2 III. This evolved type is consistent with the analysis of Shahbaz et al. (2001) and with the orbital period of 14.8 hours of the binary system.

3 DISCUSSION AND GENERAL CONCLUSIONS

NIR photometry is useful for constraining the stellar spectral type of the secondary star when the source is heavily obscured at optical wavelengths. We have determined constraints on the stellar spectral type of the counterparts of the galactic black hole candidates GRO J1655-40, GRS 1739-278, GRS 1716-249, GRS 1121-68 and GX 339-4. Our results are summarized in Table 3 and displayed in Figure 1. All the sources but GRO J1655-40 are consistent with low-mass stars as the companion star of the binary system. The position of each source in this CMD allows us to roughly estimate the evolutionary state of the secondary while its J-K colour allows us to see if the infrared emission only comes from the photosphere of the companion or is contaminated by an external source.

The most important results are our constraints on the companion stars in GRS 1716-249, GRS 1121-68 and GX 339-4, along with the weaker constraint on the companion of GRS 1739-278. For the sources GRS 1716-249 and GRS 1121-68, the location in the CMD diagram is fully consistent with their magnitudes, indicating that the infrared emission mainly emanates from the companion star, without the need for any other source of emission. The derived spectral types are respectively M0-5 V for GRS 1716-249, K0-5 V for GRS 1121-68 and F8-G2 III for GX 339-4. If the companion of GRS 1739-278 is on the main sequence then it must be a low mass star of spectral type F5 V or later. Concerning GRO J1655-40, its location, between the main sequence and giant star branches, is consistent with the sub-giant luminosity class and with this source crossing the Hertzsprung gap. However, there is a discrepancy with the optically determined F3-6 spectral type, showing that a non-stellar emission seems to contribute to the NIR flux of this source.

4 ACKNOWLEDGEMENTS

S.C. is grateful to U. Kolb for stimulating discussions, to J.A. Orosz for comments on GRO J1655-40, to C.A. Haswell

for improving the language of the manuscript and for useful suggestions, and finally to S.J.B. Burnell for a careful rereading of the manuscript. S.C. also acknowledges the anonymous referee for useful comments which allowed to improve the paper. We acknowledge the quick-look results provided by the ASM/RXTE team, used to produce the Figure 2. S.C. acknowledges support from grant F/00-180/A from the Leverhulme Trust. I.F.M. acknowledges support from CONICET/Argentina. J.M. acknowledges partial support by DG-ICYT (PB97-0903) and by Junta de Andalucía (Spain).

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Source	A_J	A_H	A_K	M_J (mag)	M_H	M_K	Spectral type
GRO J1655-40	1.10	0.59	0.44	0.77 ± 0.15	- -	0.59 ± 0.15	F3-6 IV
GRS 1739-278	3.15	1.96	1.25	≥ 1.40	-	≥ 2.5	\geq F5 V
GRS 1716-249	0.63	0.39	0.25	6.9 ± 1.2	6.9 ± 1	6.1 ± 1	M0-5 V
GRS 1121-68	0.35	0.22	0.14	4.92 ± 0.25	-	4.33 ± 0.25	K0-5 V
GX 339-4	1.05	0.65	0.42	1.41 ± 0.3	-	1.04 ± 0.3	F8-G2 III

Table 3. Results corresponding to the minimum of luminosity chosen during all our observations. We report here the absorption, and the corresponding derived absolute magnitudes. We note that the spectral type of GRO J1655-40 does not come from our analysis, but from preceding optical observations. Only the sub-giant luminosity class is consistent with the NIR observations.

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